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Influence of localized auxiliary heating on hand comfort during cold exposure

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Brajkovic, Dragan, Michel B. Ducharme, and John Frim. Influence of localized auxiliary heating on hand comfort during cold exposure. *J. Appl. Physiol.* 85(6): 2054–2065, 1998.—There is a need for a hand-heating system that will keep the hands warm during cold exposure without hampering finger dexterity. The purpose of this study was to examine the effects of torso heating on the vasodilative responses and comfort levels of cooled extremities during a 3-h exposure to −15°C air. Subjects were insulated, but their upper extremities were left exposed to the cold ambient air. The effect of heating the torso [torso-heating test (THT)] on hand comfort was compared with a control condition in which no torso heating was applied, but Arctic mitts were worn [control test (CT)]. The results indicate that mean finger temperature, mean finger blood flow, mean toe temperature, mean body skin temperature, body thermal comfort, mean finger thermal comfort, and rate of body heat storage were all significantly ($P < 0.05$) higher on average ($n = 6$) during THT. Mean body heat flow was significantly ($P < 0.05$) lower during THT. There were no significant differences ($P \geq 0.05$) in rectal temperature between CT and THT. Mean unheated body skin temperature and mean unheated body heat flow (both of which did not include the torso area in the calculation of mean body skin temperature and mean body heat flow) were also calculated. There were no significant differences ($P \geq 0.05$) in mean unheated body skin temperature and mean unheated body heat flow between CT and THT. It is concluded that the application of heat to the torso can maintain finger and toe comfort for an extended period of time during cold exposure.

protection of extremities; foot comfort; body heat transfer; local cold stress; torso heating

OUTDOOR WORKERS are often required to perform manual dexterity tasks in cold environments. This frequently necessitates the removal of protective mitts in favor of working with gloved or even bare hands. Exposure of the hands to such conditions can result in the rapid cooling of the extremities, a loss of manual dexterity (4, 11, 20, 27, 31, 34), a loss of tactile sensitivity (24, 26, 29), and an increased risk of cold injury. If the gloves or mitts are not removed, a compromise must be made between the total insulation provided by the gloves or mitts and their effect on manual dexterity. Van Dilla et al. (36) have shown that the maximum glove thickness consistent with reasonable finger dexterity (i.e., 64-mm-thick fabric) is not enough to protect the hands from a cold environment (−15°C). To counteract this problem, thin electrically heated gloves were developed over the years since World War II to allow individuals to maintain both a good deal of hand dexterity and hand comfort during extended periods of cold exposure.

The use of electrically heated gloves during cold exposure can present some difficulties. For example, electrically heated gloves may increase the chances of insidious hypothermia (28, 37). Van Someran et al. (37) state that the hands are normally colder than the rest of the body during exposure to a cold ambient environment, but during hand heating the hands are at the same temperature as the rest of the body. This results in a situation in which the human thermoregulatory system is not normally adjusted to respond effectively. Van Someran et al. suggest that when heat is applied solely to the hands the reflexes responsible for shivering may be lost because the hands play a particularly important role in the whole body thermoregulatory response to cold. As a result, hand heating may cause a nonsymptomatic decrease in core temperature. Other problems with electrically heated gloves include the following: the heating elements increase the stiffness of the gloves, thereby hampering dexterity; the robustness of the heating elements to repeated flexing in the cold can be a problem; and electrically heated gloves do not always have a uniform heat distribution.

Even with the improvements in heat distribution that have occurred over the years in the design of electrically heated gloves, "...the thermal lagging of the hand with different mass-to-surface areas (such as the fifth finger and the thumb web) makes maintenance of a uniform extremity temperature difficult" (13). Either some parts of the hand will be cold while others are comfortable, or "hot spots" will arise if those parts of the hand that cool at a faster rate are kept comfortable (13). Hot spots with auxiliary hand or foot heating can also arise when pressure enhances contact with the heating system. For example, Hickey et al. (17) found that when subjects were seated during cold exposure the electrically heated insoles worn by the subjects were thermally comfortable. However, the insoles were too hot when the subject applied pressure to the insoles by standing. Moreover, direct hand heating is an inefficient process because much of the added energy is lost to the environment through the thin insulation of the gloves.

In addition to direct auxiliary heating of the hands, past studies on hand comfort have also looked at the effects of applying local auxiliary heat to various parts of the body (1, 2, 5, 6, 12, 18, 21, 22, 25, 32, 35). However, most of these studies were done in a thermoneutral or cool environment (at temperatures of no less than 11°C). To our knowledge, only two studies have looked at the effects of auxiliary heat on hand

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comfort while subjects are barehanded during cold exposure. Auxiliary heating of the forearms while exposed to a −18°C ambient environment has been found to be unsuccessful in maintaining hand comfort (27). Rapaport et al. (30), on the other hand, found that bare hands could be kept comfortable (at a hand-skin temperature above 21°C) for a 1-h period during exposure to an ambient temperature of −34°C with the use of a full body, air-heated suit. However, the heating source for the suit was designed for laboratory use only; it did not have the mobility necessary for it to be practical in the field. Rapaport et al. also found that, in general, the hands were kept comfortable whenever there was a net body heat gain (i.e., body heat gain is greater than body heat loss), but, in some cases, the bare hands were kept comfortable for 1 h even when there was a slight negative net body heat balance.

Goldman (13) also conducted a similar experiment in which subjects were exposed to a −40°C environment while heat was provided to the torso region by using an air-heated vest. However, despite the fact that subjects wore Arctic mitts and a complete Arctic ensemble (4.3 clo), and were in a positive-heat-balance state (i.e., there was a net body heat gain), extremity comfort was not achieved. Goldman concluded that torso heating is an ineffective means of warming the extremities during cold exposure.

The above-mentioned two studies by Rapaport et al. (30) and Goldman (13) provide contrasting results as to whether extremity comfort is dependent on the body's state of heat balance. Therefore, the present study was done to provide more information about the effect of the body's state of heat balance on bare-hand comfort and body heat transfer during exposure to −15°C air. The use of active torso heating may result in a net body heat gain large enough to trigger increased circulation of blood to the extremities to dissipate the extra heat. In turn, warming of the extremities may be achieved. The relationship between extremity comfort and body heat balance obtained in the present study may provide an explanation for the contrasting results obtained by Rapaport et al. and Goldman.

METHODS

Glossary

BTC	Body thermal comfort (scale 1–13)
$C_{torso,h}$	Heated torso coefficient
$C_{torso,uh}$	Unheated torso coefficient
$C_{T_{re}}$	Rectal temperature coefficient
$C_{T_{re,h}}$	Heated body rectal temperature coefficient
$C_{T_{re,uh}}$	Unheated body rectal temperature coefficient
$C_{\bar{T}_{sk}}$	Mean body skin temperature coefficient
$C_{\bar{T}_{sk,h}}$	Mean heated body skin temperature coefficient
$C_{\bar{T}_{sk,uh}}$	Mean unheated body skin temperature coefficient
FTC	Finger thermal comfort (scale 1-13)
$\bar{H}_{body}$	Mean body heat flow (W)
$\bar{H}_{body,h}$	Mean heated body heat flow (W)
$\bar{H}_{body,uh}$	Mean unheated body heat flow (W)
$\bar{P}_{vest}$	Mean vest heater power (W)
$\bar{Q}_{fing}$	Mean middle-finger blood flow (PU)
S	Rate of body heat storage (W)
$\bar{T}_{body}$	Mean body temperature (°C)
$\bar{T}_{body,h}$	Mean heated body temperature (°C)
$\bar{T}_{body,uh}$	Mean unheated body temperature (°C)
$\bar{T}_{fing}$	Mean middle-finger skin temperature (°C)
$\bar{T}_{toe}$	Mean large-toe skin temperature (°C)
$\bar{T}_{sk}$	Mean body skin temperature (°C)
$\bar{T}_{sk,uh}$	Mean unheated body skin temperature (°C)
$\bar{T}_{sk,h}$	Mean heated body skin temperature (°C)

Subjects

Six healthy, nonsmoking male volunteers with the following characteristics were recruited (mean ± SD): age 28.7 ± 6.2 yr, height 177.7 ± 7.2 cm, weight 75.8 ± 2.4 kg, and body surface area 1.93 ± 0.07 m^2. Body surface area was calculated by using the formula of DuBois and Dubois (8). All subjects were informed of the experimental protocol and were granted medical approval to participate before being asked for their written consent. In addition, subjects were asked to avoid caffeine, alcohol, and intense physical activity for at least 12 h before the test. Subjects with a strong dependency on these agents were not accepted for the study.

Experimental Protocol

All subjects were exposed to a familiarization run and then randomly to two experimental tests: a torso-heating test (THT) and a control test (CT). All exposures were 1 wk apart and at the same time of the day.

THT. During THT, the subjects were asked to sit on a wooden bench in a cold chamber maintained at −15°C (wind ~2 km/h) for 3 h. Subjects entered the chamber barehanded; their mean finger temperature ($\bar{T}_{fing}$; average of middle-finger temperatures of left and right hand) was monitored until it reached 15°C (cooling phase). A $\bar{T}_{fing}$ of 15°C was used as the criterion for the initiation of rewarming because it has been found that finger dexterity is decreased when $\bar{T}_{fing}$ falls below 15°C (11). At this point, an attempt was made to indirectly rewarm the fingers by heating the torso to 42 ± 0.5°C with an electrically heated vest for the remainder of the test (rewarming phase). During the test, the subjects wore the first two layers of the new Canadian Forces (CF) Arctic clothing ensemble, which consisted of a fleece garment (jacket and pants) and an uninsulated jacket and pants. A thin pair of long cotton underwear were also worn under the fleece pants. Standard CF mukluks, woolen socks, and a balaclava were also worn. The clothing (excluding the long cotton underwear) provided 2.6 clo (0.4 $m^2 \cdot k^{-1} \cdot W^{-1}$) of insulation.

The electrically heated vest consisted of 10 Kapton insulated flexible heaters (Omega Engineering, Stamford, CT) fixed around the torso as follows: two heaters (each 12 × 20 cm) on the chest, two heaters on the abdomen (each 8 × 30 cm), one heater under each armpit (each 8 × 20 cm), two heaters over the shoulder area (each 8 × 30 cm), and two heaters on the back (each 15 × 30 cm). The heaters covered a total area of 0.266 m^2. The heaters were not in direct contact with the skin but inside a fire-resistant pocket made of

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Nomex fabric. In addition, a 1-cm layer of Thinsulate insulation was placed inside the pocket on the outer surface of the heater. The Thinsulate insulation was covered by a piece of reflective Mylar to help reflect the radiative heat back to the torso. Once the heaters were placed inside the pockets, the pockets were sewn together to form a vest that covered a total area of 0.366 m^2. A tight, short-sleeved Lycra body suit that extended to midthigh level was worn over the heaters to optimize the contact between the skin and the heaters. Preselected voltages were sent by five current-limiting power supplies (two model 6030A, 0–200 V/0–17 A, 1,000 W; three model 6034A, 0–60 V/0–10 A, 200 W; Hewlett-Packard) to the five pairs of heaters to achieve a skin temperature of 42 ± 0.5°C under each heater. The power supplies were controlled by a computer.

By the manual adjustment of the power delivered to the heaters, skin temperature under the heaters was kept at 42 ± 0.5°C to avoid any skin damage by the heat. This skin temperature is considered safe because it has been shown by Davies (7) and Hardy (16) that 45°C is the critical skin temperature to produce cutaneous burn and to evoke pain. To ensure that the skin temperature under the heaters did not reach 45°C at any time, the computer turned off the heater completely if skin temperature reached 44°C.

CT. The CT was identical to the THT except for the rewarming phase. During the CT rewarming phase, CF Arctic mitts were donned after $\bar{T}_{fing}$ reached 15°C. No heat was delivered to the torso via the electrically heated vest.

THT familiarization run. The subjects were familiarized with the equipment and procedures that were used during THT. In particular, the approximate torso heater power required to maintain the skin temperature underneath the heating vest at 42°C during THT was established. The subjects were fully dressed with the sensors, heaters, and clothing to be used during the test, then exposed to a 1-h exposure to −15°C air. The standard procedures of THT were followed.

Physiological Parameters Measured

Finger skin temperature (T_{fing}) was measured by using a thermistor (YSI 44004 series; Yellow Springs Instruments, Yellow Springs, OH) and finger skin blood flow ($\dot{Q}_{fing}$) by using a 780-nm laser Doppler flowmeter probe (PF4001 laser Doppler flowmeter, Perimed, Stokholm, Sweden). The probes were placed side by side on the middle fingertips of both hands. The unit of measurement used to represent the skin blood flow is the perfusion unit (PU), a relative unit of blood flow. A calibration standard is used to adjust the laser Doppler flowmeter readings to coincide with the readings obtained with a motility standard. Toe skin temperature (T_{toe}) was measured by using a thermistor (YSI 44004 series; Yellow Springs Instruments) placed on the medial side of the big toe of each foot. Body thermal comfort (BTC) and mean finger thermal comfort (FTC) were measured every 15 min (starting at *time 0*) by using the McGinnis comfort scale (19). During CT and THT, rectal temperature (T_{re}) was measured via a thermistor (Pharmaseal 400 series, Baxter, Valencia, CA) inserted 15 cm beyond the anal sphincter. Mean body skin temperature ($\bar{T}_{sk}$) and mean body heat flow ($\bar{H}_{body}$) were measured by using heat flux transducers (HFTs) with embedded thermistors [model HA13–18–10-P(C), Concept Engineering, Old Saybrook, CT]. The mean body heat flux (in $W \cdot m^{-2}$) for each subject was multiplied by the surface area of the subject (m^2) to determine $\bar{H}_{body}$ (in W). The HFTs were recalibrated, and the values were corrected for the decreased heat flux measurement that occurs because of the thermal resistance of the HFTs (10). The HFTs were placed on the body by using a modified version of the HFT sites used by Hardy and DuBois (14). In this modified version, 10 HFTs were used to represent the heat flux of the heated portion of the body and 10 HFTs were used to represent the unheated regions of the body. The heat flux and skin temperature weighting coefficients for the torso region originally used in the Hardy and DuBois system were modified to represent the heated and unheated areas of the torso.

The "heated region of torso coefficient" ($C_{torso,h}$) for each subject was calculated by dividing the vest area (0.366 m^2) by the entire body surface area (m^2). The insulated 0.366-m^2 vest area was used to represent the actively heated region of the torso instead of the 0.266-m^2 heater area because it was assumed that the skin temperature within 1–2 cm of the edge of the heaters was very close to the skin temperature directly underneath the heaters because of the reflective Mylar and Thinsulate insulation (covering an area of 0.366 m^2) that covered the heaters. Once $C_{torso,h}$ was calculated, the front and back "unheated region of torso coefficients" ($C_{torso,uh}$) for each subject were calculated in the following manner: $C_{torso,uh} = (0.35 - C_{torso,h})/2$, where 0.35 is the coefficient Hardy and DuBois (14) used to represent the torso area.

The $\bar{T}_{sk}$ calculation during THT was heavily influenced by the skin thermistors under the heating vest; therefore, any significant differences observed in $\bar{T}_{sk}$ between CT and THT may not exist if the torso is not included in the calculation. Because of this possibility, a mean unheated body skin temperature ($\bar{T}_{sk,uh}$) was also calculated. $\bar{T}_{sk,uh}$ did not include any skin thermistor sites that were on the torso. For the same reason, because the calculation $\bar{H}_{body}$ is heavily influenced by the HFTs under the heating vest, a mean unheated body heat loss ($\bar{H}_{body,uh}$) was calculated.

Mean heated body heat flux ($\bar{H}_{body,h}$) in $W \cdot m^{-2}$ and mean heated body skin temperature ($\bar{T}_{sk,h}$) were measured by placing a HFT embedded with a thermistor [HA-13–18–10-P(C), Concept Engineering] under each of the heaters that make up the vest. The average skin temperatures under each of the five pairs of heaters (chest, abdomen, side, shoulder, and back) were calculated, and the five values were averaged to establish $\bar{T}_{sk,h}$. $\bar{H}_{body,h}$ (in $W \cdot m^{-2}$) was multiplied by the surface area of the vest (0.366 m^2) to determine mean

heated body heat flow ($\dot{H}_{body,h}$, in W). $\dot{H}_{body,h}$ provides a measurement of the heat delivered to the torso area directly underneath the vest, whereas the mean vest heater power ($\bar{P}_{vest}$, in W; voltage × current of the 5 power supplies) is the power needed to deliver the desired $\dot{H}_{body,h}$. $\bar{P}_{vest}$ is greater than $\dot{H}_{body,h}$ because a portion of the heat from the heaters is lost to the ambient environment. Body heat storage (S; in kJ) was calculated during both CT and THT by using the thermometric method described by Burton (3). S was calculated as follows

$$S_t = 3.47 \cdot m_{body} \cdot \Delta\bar{T}_{body}$$

where 3.47 is the specific heat of the tissues, m_{body} is the body mass of the individual, and $\Delta\bar{T}_{body}$ is the change in mean body temperature at time t from the initial mean body temperature at *time 0*. This was calculated as follows

$$\Delta\bar{T}_{body} = \bar{T}_{body_t} - \bar{T}_{body_0}$$

$\bar{T}_{body}$ was calculated as the weighted sum of T_{re} and $\bar{T}_{sk}$. In the past, the weighting coefficients have been adjusted to reflect the ambient temperature. That is, the core is given more weighting in hotter environments and less weighting in cooler environments. For example, the $\bar{T}_{body}$ of an individual exposed to cool conditions (nude, 23°C ambient environment) under steady-state conditions may be estimated by the following relationship

$$\bar{T}_{body} = 0.67T_{re} + 0.33\bar{T}_{sk} \quad (3)$$

whereas the $\bar{T}_{body}$ of an individual exposed to a thermoneutral environment (nude, 28–30°C environment) and a hot environment (nude, 33–36°C ambient environment) under steady-state conditions may be estimated by the following relationships (Ref. 15 and Refs. 9 and 15, respectively), respectively

$$\bar{T}_{body} = 0.8T_{re} + 0.2\bar{T}_{sk}$$

$$\bar{T}_{body} = 0.9T_{re} + 0.1\bar{T}_{sk}$$

The above equations are appropriate to steady-state conditions. In the present experiment, the subjects were either cooling over time (during CT) or subjected to heat being delivered to the torso after a short period of cooling (during THT; i.e., the subjects were not likely in a steady state). Hence the use of any one equation was deemed inappropriate. Livingstone (23) found that, under non-steady-state conditions, the weighting coefficients for T_{re} and $\bar{T}_{sk}$ should be adjusted not only for ambient temperature but also for time. In the present study, these adjustments were made after the data were collected.

During CT, the change in T_{re} coefficient ($C_{T_{re}}$) over time was determined every minute during the 3-h exposure by using a two-step approach. $C_{T_{re}}$ was first determined every 10 min by using the following relationship

$$C_{T_{re}} = \frac{(\Delta\bar{T}_{body} - 0.8T_{re_i} - 0.2\bar{T}_{sk_i} + \bar{T}_{sk_f})}{(\bar{T}_{sk_f} - T_{re_f})}$$

where f and i are final and initial, respectively.

$\Delta\bar{T}_{body}$ in the above equation was not derived from thermometry calculations but rather was directly measured during a 3-h whole body air calorimetry experiment (unpublished observations, personal communication, J. W. Snellen, 1996), in which T_{re} and $\bar{T}_{sk}$ responses of the subjects were very similar to the T_{re} and $\bar{T}_{sk}$ responses observed in the present experiment. Therefore, the cooling curve from Snellen's experiment was applied to the present data to determine $C_{T_{re}}$. When $C_{T_{re}}$ was plotted as a function of time, an exponential decrease in $C_{T_{re}}$ was observed. An exponential curve fit was calculated, and the equation of the curve was determined (cooling curve). The cooling curve was then applied to each set of T_{re} and $\bar{T}_{sk}$ data for each subject for the calculation of $\Delta\bar{T}_{body}$. During CT, $C_{T_{re}}$ decreased exponentially from 0.8 to 0.66. A $C_{T_{re}}$ of 0.8 was chosen as the starting point because the $\bar{T}_{sk}$ of the subjects (on entering the chamber) in the present study was similar to the $\bar{T}_{sk}$ of nude subjects exposed to a thermoneutral environment (28°C ambient temperature; personal communication, J. W. Snellen, 1996). It is interesting to note that the exponential decrease in $C_{T_{re}}$ was almost identical to the exponential decrease in $\bar{T}_{sk}$. Therefore, it appears as though the $\bar{T}_{sk}$ response may be used to establish the rate of change in $C_{T_{re}}$.

During THT, the calculation of $\Delta\bar{T}_{body}$ by using thermometry is complicated by the fact that some parts of the body are cooling while others (i.e., the area covered by the vest) are being heated. This problem was dealt with by treating the body as two separate regions (i.e., the heated and the unheated region of the body), so that

$$\Delta\bar{T}_{body(THT)} = \bar{T}_{body,uh} + \bar{T}_{body,h}$$

where $\bar{T}_{body,uh}$ is the weighted sum of $\bar{T}_{sk,uh}$ and T_{re}, and $\bar{T}_{body,h}$ is the weighted sum of $\bar{T}_{sk,h}$ and T_{re}. $C_{T_{re}}$ is different for the heated and unheated regions of the body. The changes in $C_{T_{re}}$ over time for the two regions will now be examined in detail. For the unheated region of the body, the CT cooling curve described earlier was used to represent the change in $C_{T_{re}}$ over time because $\bar{T}_{sk,uh}$ during THT was not significantly different ($P \geq 0.05$) from that during CT. The $C_{T_{re}}$ for the unheated region of the body was defined as $C_{T_{re,uh}}$. For the heated region of the body, the CT cooling curve was applied up to the point at which the heating vest was turned on. At that point, the change in $C_{T_{re}}$ over time followed a heating curve. The heating curve is based on the observation that during CT, the rate of decrease in $\bar{T}_{sk}$ closely mimics the rate of decrease in $C_{T_{re}}$. Therefore, it was assumed that the rate of increase in $C_{T_{re}}$ for the heated region of the body closely mimics the exponential increase in skin temperature under the heating vest (i.e., $\bar{T}_{sk,h}$). The $C_{T_{re}}$ for the heated region of the body was defined as $C_{T_{re,h}}$.

Therefore, by using the above information, $\overline{T}_{body,uh}$ and $\overline{T}_{body,h}$ during THT were calculated in the following manner (by using 0.366 m^2 to represent the heated area of the torso)

$$\overline{T}_{body,uh(THT)} = [(C_{T_{re,uh}} \cdot T_{re} + C_{\overline{T}_{sk,uh}} \cdot \overline{T}_{sk,uh}) \cdot [1 - (0.366 \div A_D)]]$$

$$\overline{T}_{body,h(THT)} = [(C_{T_{re,h}} \cdot T_{re} + C_{\overline{T}_{sk,h}} \cdot \overline{T}_{sk,h}) \cdot (0.366 \div A_D)]$$

where $C_{T_{re,uh}}$, $C_{\overline{T}_{sk,uh}}$, and $\overline{T}_{sk,uh}$ are the $C_{T_{re}}$, $\overline{T}_{sk}$ coefficient, and $\overline{T}_{sk}$ for the unheated region of the body, respectively; A_D is the Hardy and DuBois (14) body surface area (in m^2); $C_{T_{re,h}}$, $C_{\overline{T}_{sk,h}}$, and $\overline{T}_{sk,h}$ are the $C_{T_{re}}$, $\overline{T}_{sk}$ coefficient, and $\overline{T}_{sk}$ for the heated region of the body, respectively.

After S was calculated by using the above procedures to calculate $\overline{T}_{body}$, the rate of body heat storage ($\dot{S}$, in W) during the exposure was calculated at every minute

$$S_t = \frac{S_t - S_{t-1}}{60} \cdot 1{,}000$$

Measurements of $\overline{T}_{fing}$, $\overline{T}_{toe}$, T_{re}, $\overline{T}_{sk}$, $\overline{T}_{sk,uh}$, $\overline{H}_{body}$, and $\overline{H}_{body,uh}$ were made five times per minute over the course of 3 h by using a data-acquisition system (model 3497A data-acquisition/control unit; Hewlett-Packard). An average value was printed out each minute.

Statistical Analyses

Because of differences in the rates of finger cooling among subjects, all data were time shifted so that the start of rewarming (i.e., $\overline{T}_{fing}$ = 15°C) occurred at *time 0* (t_0). To include all six subjects in the analyses for both CT and THT, the time range for analyses was restricted to the interval t_{-10} to t_{124}; extended analyses (with n = 5) were possible between t_{-10} and t_{151}.

To reduce the data set to a more manageable size, average values over 5 min were calculated for each measured variable and were assigned to the middle time point of each 5-min interval (e.g., t_2, t_7, and t_{12}..., are average values for the intervals t_0 to t_4, t_5 to t_9, and t_{10} to t_{14}..., and so on).

A two-way ANOVA for repeated measures (SuperAnova, Abacus Concepts) with heating condition and time as the independent variables was used to compare conditions CT and THT for the dependent measurements $\overline{T}_{fing}$, $\overline{Q}_{fing}$, $\overline{T}_{toe}$, T_{re}, $\overline{T}_{sk}$, $\overline{T}_{sk,uh}$, $\overline{H}_{body}$, $\overline{H}_{body,uh}$, BTC, FTC, and $\dot{S}$. Results were considered statistically significant at $P < 0.05$ (by using the Greenhouse-Geisser adjustment for repeated measures).

If a significant treatment × time interaction existed in the two-way ANOVA for the repeated-measures test, a contrast test was performed every 5 min from t_{-10} to t_{124} (using n = 6) and from t_{-10} to t_{151} (using n = 5) to determine the time interval at which a significant difference existed between CT and THT.

A two-way ANOVA for the repeated-measures test was used to determine whether significant differences existed in left and right T_{fing} and T_{toe} responses from t_{-10} to t_{124} (using n = 6) and from t_{-10} to t_{151} (using n = 5) during CT and THT.

RESULTS

The variables described below were measured during both CT and THT. The data are presented as means ± SE (n = 6) for each minute during the time period t_{-10} to t_{151} (see Figs. 1–9, which identify where n is reduced from 6 to 5). $\dot{S}$ is presented as 5-min averages during the time period t_{-3} to t_{147}. $\overline{T}_{fing}$, $\overline{Q}_{fing}$, $\overline{T}_{toe}$, $\overline{T}_{sk}$, BTC, FTC, and $\dot{S}$ were all significantly higher ($P < 0.05$) during most of the THT rewarming phase from t_0 to t_{151}. $\overline{H}_{body}$ was significantly lower ($P < 0.05$) during the THT rewarming phase. There were no significant differences ($P \geq 0.05$) in T_{re}, $\overline{T}_{sk,uh}$, and $\overline{H}_{body,uh}$ between CT and THT during the rewarming phase. Tests for statistically significant differences between CT and THT were not done for data past t_{151} because of the decreasing n value that resulted from time-shifting the data. There were no significant differences ($P \geq 0.05$) between the CT and THT conditions for the 10-min period before t_0 for any of the measured variables. There were also no significant differences ($P \geq 0.05$) in the $\overline{T}_{fing}$ and $\overline{T}_{toe}$ responses (for n = 6) between the left and right finger and/or toe temperatures during both CT and THT. Therefore, the left and right finger and/or toe temperatures were averaged for all six subjects.

In an examination of the figures presented in this paper, a discontinuity is often observed at t_{124} during CT and THT. This is because of a sudden increase in the overall mean value of the measured variable that resulted when one subject ended the cold exposure early because of an uncomfortable $\overline{T}_{fing}$ (i.e., the discontinuity is because of a decrease in the n value from 6 to 5). It was later observed that this subject had an abnormally high susceptibility to finger cooling. The following subsections provide a descriptive summary of each measured variable from t_{-10} to t_{124} for CT and THT (during which time n = 6) even though the n = 5 data are included in the figures. The n = 5 data were included to illustrate that the general trend for all measured parameters remained the same up to t_{151} for the five subjects who remained in the experiment.

$\overline{P}_{vest}$ and $\overline{H}_{body,h}$

The first 35-min period of heating was used to achieve a stable skin temperature of 42°C underneath the heating vest. A $\overline{P}_{vest}$ of 108 W was used to deliver a $\overline{H}_{body,h}$ of −95 W during THT (Fig. 1) (in relation to heat flow, a positive value represents a heat loss, and a negative value represents a heat gain). During CT, no heat was delivered to the torso, which resulted in a $\overline{H}_{body,h}$ of 25 W (Fig. 1). It should be noted that a decrease in $\overline{P}_{vest}$ occurred during THT from t_{113} to t_{114} because the vest was accidentally turned off in one subject for a 1-min period. However, the change in $\overline{H}_{body,h}$ (for n = 6) was minimal because the $\overline{P}_{vest}$ was immediately restored after the 1-min period.

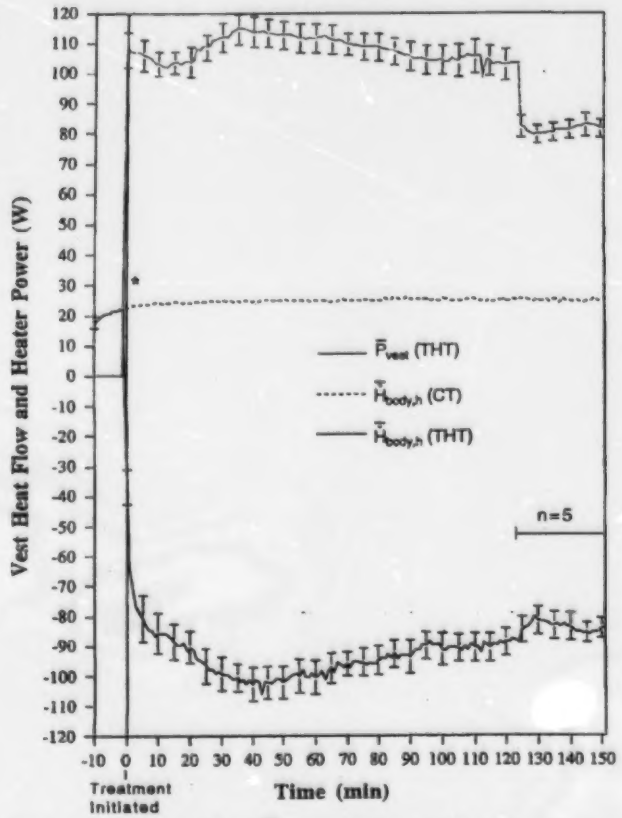

Fig. 1. Mean vest heat flow ($\bar{H}_{body,h}$; control test (CT) and torso-heating test (THT)] and mean vest heater power ($\bar{P}_{vest}$; THT) from time t_{-10} to t_{151} at −15°C. Values are means ± SE; $n = 6$ unless otherwise noted. *Time of 1st significant difference between THT and CT ($P < 0.05$).

$\bar{T}_{fing}$

During both CT and THT, $\bar{T}_{fing}$ decreased from 31 to 15°C between t_{-10} and t_0 when rewarming was initiated. During the CT rewarming phase, $\bar{T}_{fing}$ increased to 19°C during the first 7 min, then decreased to 13°C by t_{50}, at which time it leveled off (Fig. 2). During the THT rewarming phase, $\bar{T}_{fing}$ continued to cool for the first 4 min, then increased rapidly to 26°C at t_{50}. $\bar{T}_{fing}$ cycled between 23 and 29°C until t_{100}, then stabilized again at 23°C until t_{124} (Fig. 2).

$\bar{Q}_{fing}$

During the CT and THT rewarming phases, $\bar{Q}_{fing}$, followed the same general trend as $\bar{T}_{fing}$. However, the changes in $\bar{Q}_{fing}$ preceded the changes in $\bar{T}_{fing}$ (Fig. 3). The sudden increase in $\bar{Q}_{fing}$ that occurred at t_{90} during CT was due to the accidental movement of the laser Doppler $\bar{Q}_{fing}$ probe in one subject.

$\bar{T}_{toe}$

$\bar{T}_{toe}$ decreased during both the CT and THT rewarming phases. However, the rate of decrease was much slower during THT. During the CT rewarming phase, $\bar{T}_{toe}$ decreased to 13°C by t_{124}, with no indication of an impending plateau (Fig. 4). During the THT rewarming phase, $\bar{T}_{toe}$ decreased to 22°C by t_{100}, at which point it leveled off (Fig. 4).

T_{re}

During the CT rewarming phase, T_{re} decreased from 37.15 to 36.72°C between t_0 and t_{124}, whereas it remained stable, on average, at 37.22°C during the entire THT rewarming phase (Fig. 5). Evidence of insidious hypothermia has been observed in some studies in which well-insulated subjects were exposed to a cold environment while direct heating was applied to the extremities (13, 17). In the present study, there was no change in T_{re} during the rewarming phase. Therefore, there does not appear to be any risk of insidious hypothermia when torso heating is applied for short durations (up to 3 h).

$\bar{T}_{sk}$ and $\bar{T}_{sk,uh}$

$\bar{T}_{sk}$ gradually decreased to 27.2°C by t_{124} during the CT rewarming phase. However, during the THT re-

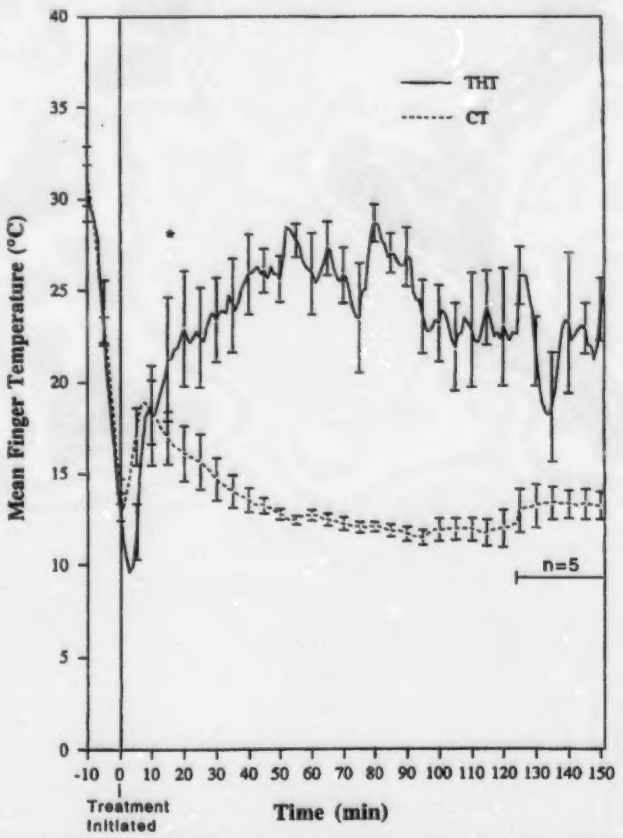

Fig. 2. Mean middle-finger temperature from t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. *Time of 1st significant difference between THT and CT. Mean middle-finger temperature was significantly higher ($P < 0.05$) during THT from * until t_{151}.

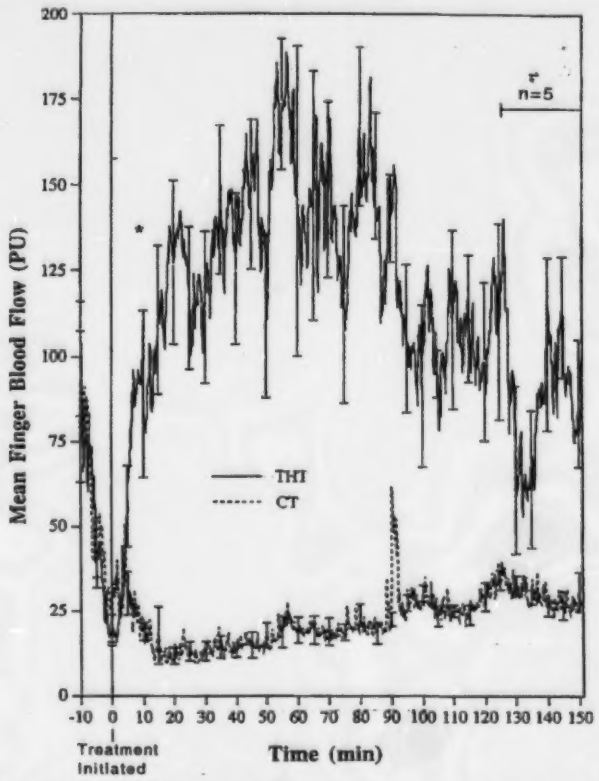

Fig. 3. Mean middle-finger blood flow from t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; n = 6 unless otherwise noted. *Time of 1st significant difference between THT and CT. Mean middle-finger blood flow was significantly higher ($P < 0.05$) during THT from * until t_{151}. Unit of measurement used to represent skin blood flow is perfusion unit (PU), which is a relative unit of blood flow.

warming phase, $\overline{T}_{sk}$ increased by 1°C during the first 10 min and then decreased to 30.5°C by t_{124} (Fig. 6). During the CT rewarming phase $\overline{T}_{sk,uh}$ gradually decreased to 25.5°C by t_{124}, whereas during the THT rewarming phase it decreased to 26.8°C over the same time period (Fig. 6).

$\overline{H}_{body}$, $\overline{H}_{body,uh}$

With the exception of the first 35 min of the rewarming phase, $\overline{H}_{body}$ remained relatively stable at 165 W during CT. During THT, $\overline{H}_{body}$ remained stable at 68 W (Fig. 7). $\overline{H}_{body,uh}$ remained relatively stable at 119 W from t_{35} to t_{124} during both CT and THT. It is interesting to note that the reduction in $\overline{H}_{body}$ that occurred during THT, relative to CT (i.e., 165 W − 68 W = 97 W), is very similar to the 95-W $\overline{H}_{body,h}$ that was provided during THT.

BTC

In general, during the CT rewarming phase, subjects felt progressively colder during the test (a comfort rating of −4 or "cold" was reported by t_{120}), whereas during the entire THT rewarming phase, subjects felt either "comfortable" or "warm, but fairly comfortable" (comfort rating between 7 and 8) (Fig. 8).

Mean FTC

During the first 30 min of the rewarming phase mean FTC increased from four ("cold") to six ("cool, but fairly comfortable") during CT and THT. During CT, from t_{30} to t_{120}, mean FTC gradually decreased to an uncomfortable level (comfort rating between 3 and 4; i.e., the fingers felt either "very cold" or "cold"), whereas during THT, from t_{30} to t_{120}, the fingers felt either "cool, but fairly comfortable" or "comfortable" (comfort rating between 6 and 7).

$\dot{S}$

During the CT rewarming phase, $\dot{S}$ was, on average, −67 W from t_{35} to t_{124}. However, $\dot{S}$ fluctuated between −140 and 20 W during this time period (Fig. 9). The average SE and SD from t_{35} to t_{124} for $\dot{S}$ were 20 and 49 W, respectively. During the THT rewarming phase, $\dot{S}$ was, on average, −48 W from t_{35} to t_{124}. However, $\dot{S}$

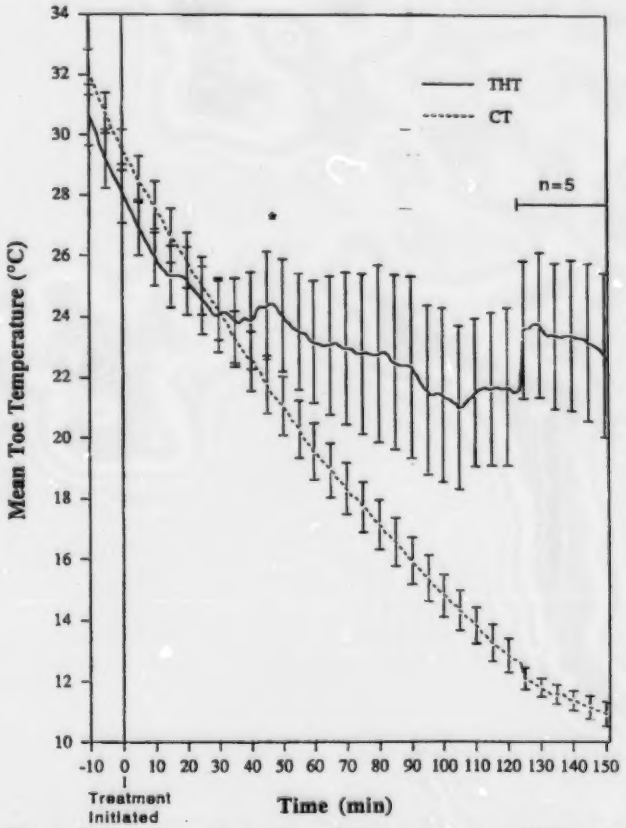

Fig. 4. Mean large-toe temperature from t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; n = 6 unless otherwise noted. *Time of 1st significant difference between THT and CT. Mean large-toe temperature was significantly higher ($P < 0.05$) during THT from * until t_{151}.

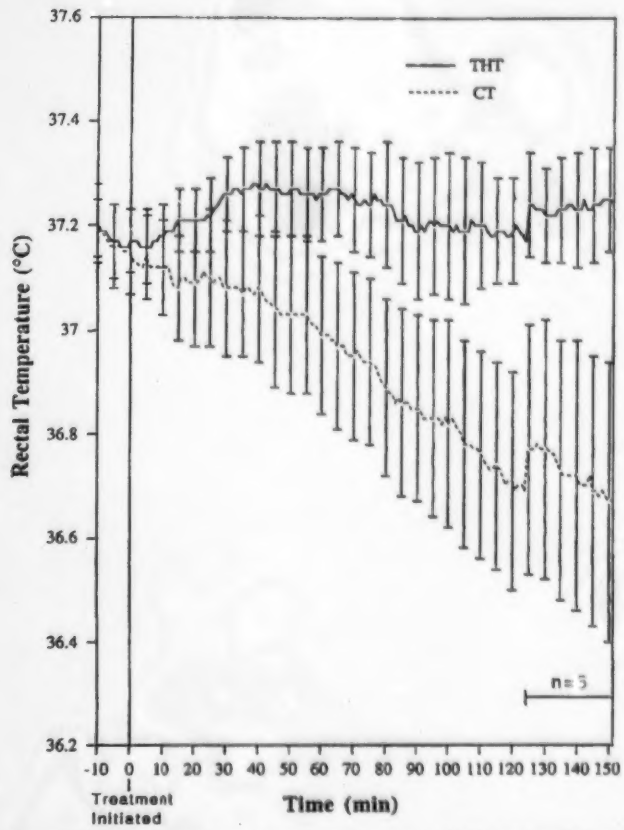

Fig. 5. Rectal temperature from t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. There was no significant difference ($P \geq 0.05$) in rectal temperature between CT and THT from t_0 to t_{151}.

fluctuated between −120 and 40 W during this time period (Fig. 9). The average SE and SD from t_{35} to t_{124} for $\dot{S}$ were 33 and 81 W, respectively. $\dot{S}$ was significantly different ($P < 0.05$) from 0 W for both CT and THT.

DISCUSSION

The results indicate $\overline{T}_{fing}$, $\overline{Q}_{fing}$, $\overline{T}_{toe}$, $\overline{T}_{sk}$, BTC, FTC, and $\dot{S}$ were all significantly higher ($P < 0.05$) during the THT rewarming phase than during the CT rewarming phase. $\overline{H}_{body}$ was significantly ($P < 0.05$) lower during the THT rewarming phase. In addition, there were no significant differences ($P \geq 0.05$) in T_{re}, $\overline{T}_{sk,uh}$, and $\overline{H}_{body}$ between the CT and THT rewarming phases. Overall, torso heating can keep the body, fingers, and toes comfortable for an extended period of time during exposure to −15°C air.

$\dot{S}$

During THT, there was, on average, a net body heat loss of 48 ± 33 W during the time period from t_{35} to t_{124} and a steady skin temperature of 42 ± 0.5°C underneath the vest. However, despite this negative state of body heat balance, both the hands and feet were maintained at a comfortable level (i.e., $\overline{T}_{fing}$ and $\overline{T}_{toe}$ of 25°C). This finding suggests that the extremity rewarming can occur even if $\dot{S}$ is significantly < 0 W ($P < 0.05$). However, before any conclusions can be drawn regarding the relationship between $\dot{S}$ and extremity comfort, the accuracy of the thermometric method to determine $\dot{S}$ must also be considered.

First, the $\dot{S}$ fluctuations themselves most likely do not provide a true representation of the actual $\dot{S}$ changes that occur within the body because it is unlikely that such fluctuations occur so frequently and to such a great extent (see Fig. 9). Second, when the thermometric method is used, it is generally assumed that $C_{T_{re}}$ and $C_{\overline{T}_{sk}}$ of the subject do not change during the course of the experiment. In the present experiment, subjects wore a heating vest and the first two layers of the CF Arctic clothing ensemble. When the subjects entered the cold chamber, no torso heating was applied during THT for the first 10–29 min of the exposure. Therefore, the core-to-shell weighting could

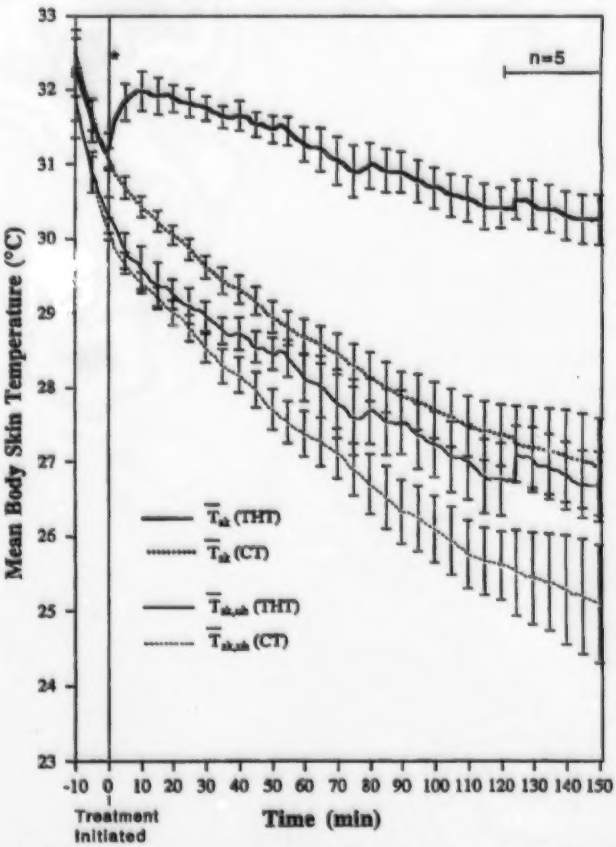

Fig. 6. Mean body skin temperature ($\overline{T}_{sk}$) and mean unheated body skin temperature ($\overline{T}_{sk,uh}$) from t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. *Time of 1st significant difference between THT and CT for mean body skin temperature. Mean body skin temperature was significantly higher ($P < 0.05$) during THT from * until t_{151}. There was no significant difference ($P \geq 0.05$) in mean unheated body skin temperature between CT and THT from t_0 to t_{151}.

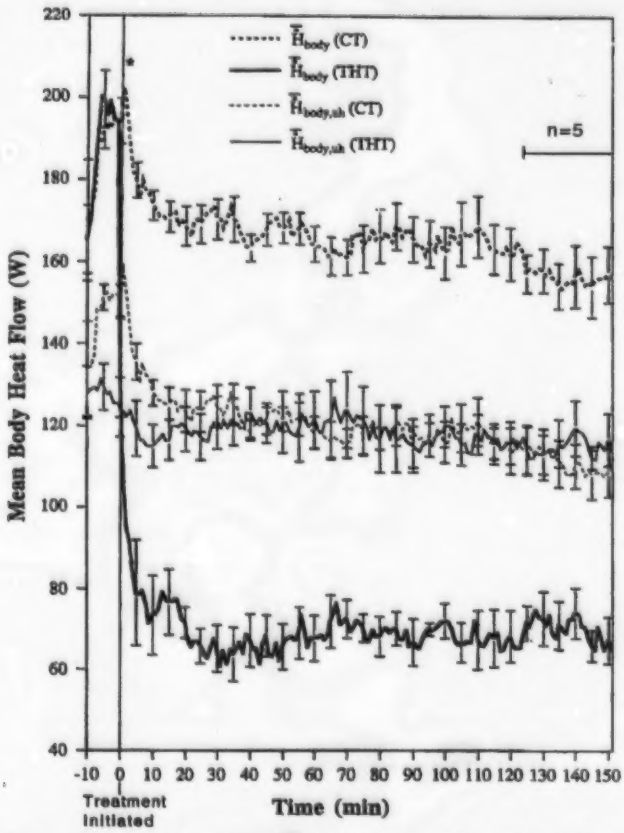

Fig. 7. Mean body heat flow ($\bar{H}_{body}$) and mean unheated body heat flow ($\bar{H}_{body,sh}$) for t_{-10} to t_{151} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. *Time of 1st significant difference between THT and CT. Mean body heat flow was significantly lower ($P < 0.05$) during THT from * until t_{151}. There was no significant difference ($P \geq 0.05$) in mean unheated body heat flow between CT and THT from t_0 to t_{151}.

well have changed during the course of the experiment. Hence, in the present study, the weighting coefficients were adjusted over time by allowing the $C_{T_{re}}$ to follow the $\bar{T}_{sk}$ responses in an attempt to more properly represent the $\Delta\bar{T}_{body}$ over time. Despite this improvement in the thermometric method, the true $\Delta\bar{T}_{body}$ were not directly verified in the present experiment. Therefore, there is a chance that these adjustments are not representative of the true $\Delta\bar{T}_{body}$. Last, an inaccuracy in the estimation of $\dot{S}$ during THT can be used to explain the finding that, despite a $\bar{H}_{body}$ of 165 W during CT and a $\bar{H}_{body}$ of 68 W during THT, $\dot{S}$ differed by only 19 W between the two conditions (i.e., −67 W during CT vs. −48 W during THT).

The thermometric method used in the present study to calculate $\dot{S}$ can be compared with a theoretical partitional calorimetry calculation of $\dot{S}$. For example, assuming that the metabolic rate was ~100 W during each condition, calculating this value into the heat balance equation would result in an $\dot{S}$ of about −65 W during CT (not taking into account any evaporative losses from the body). This theoretical value of $\dot{S}$ is very close to the $\dot{S}$ value obtained by thermometry (−67 W). However, during THT, the measured value of $\dot{S}$ (−48 W) is not close to the theoretical value of $\dot{S}$ (+32 W). Because the calculated $\dot{S}$ by using thermometry is most likely a crude estimation of the actual $\dot{S}$, further research, using better methods of determining body heat balance (e.g., using partitional calorimetry or direct calorimetry), is needed before any conclusions relating extremity comfort to body heat balance can be made.

The two primary measured variables used in the calculation of $\dot{S}$ are $\bar{T}_{sk}$ and T_{re}. Hence the significantly ($P < 0.05$) higher $\dot{S}$ observed during THT, compared with CT, can be attributable mainly to the significantly ($P < 0.05$) higher $\bar{T}_{sk}$ maintained during THT because there was no significant ($P \geq 0.05$) difference in the T_{re} response between CT and THT.

It is worthwhile noting that Rapaport et al. (30) used partitional calorimetry to calculate $\dot{S}$, whereas Goldman (13) used thermometry to calculate $\dot{S}$. Rapaport et al. found that, in general, extremity comfort was maintained for subjects with an $\dot{S} \geq 0$. Goldman, on the other hand, found that extremity comfort could not be achieved despite a net body heat gain of 84 W (based on

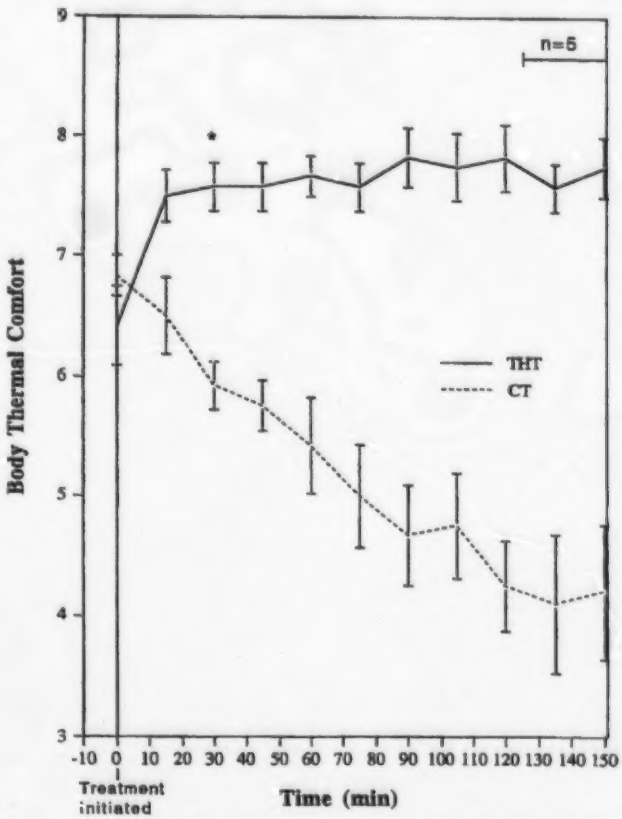

Fig. 8. Body thermal comfort for t_0 to t_{151} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. *Time of 1st significant difference between THT and CT. Body thermal comfort was significantly higher ($P < 0.05$) during THT from * until t_{151}.

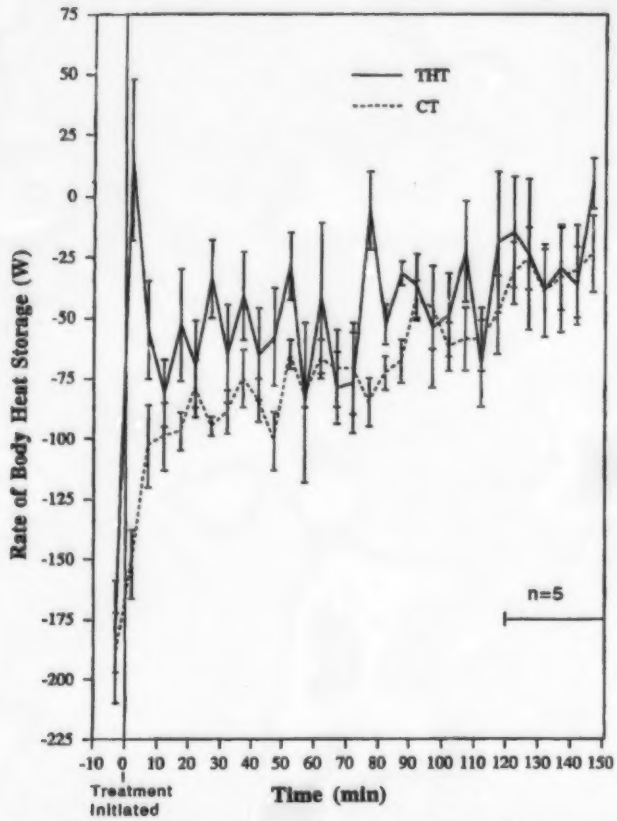

Fig. 9. Body heat storage for t_{-3} to t_{147} at −15°C during CT and THT. Values are means ± SE; $n = 6$ unless otherwise noted. Body heat storage was significantly higher ($P < 0.05$) during THT from t_7 to t_{147}. Body heat storage for CT and THT was significantly different ($P < 0.05$) from 0 W.

a 2-m² body surface area). If extremity comfort is directly related to a body heat balance ≥ 0, this would suggest that Goldman's thermometry calculations may have overestimated $\dot{S}$ whereas, in the present study, $\dot{S}$ may have been underestimated. It should also be noted that Rapaport et al. (30) found that, in one experiment, bare-hand comfort could be maintained (average hand-skin temperature between 25 and 29°C) for 1 h during exposure to −34°C air, even when there was a $\dot{S}$ of −23 W. The data of Rapaport et al. support our finding that the fingers and toes could be kept comfortable during torso heating even when $\dot{S}$ is negative.

T_{re}

In the present study, T_{re} remained stable during the entire rewarming phase. This finding is in agreement with the results of Goldman (13), who also reported a stable T_{re} during torso heating. However, he did not report the actual value. An increased T_{re} was not observed during torso heating, most likely because the increased heat gain by the torso was matched by a corresponding heat loss in the rest of the body. Because the hands and feet act as natural radiators of the body, a vasodilative response occurred in these regions to dissipate the extra heat gained by the torso (see Fig. 3). In doing so, the core temperature was maintained at a constant level and the hands warmed. In other words, the indirect vasodilative responses observed appear to be a physiological mechanism by which the body protects itself from an increase in core temperature and possible hyperthermia. This explanation may also be used to explain the contrasting results of Veghte (38). Veghte found that during exposure to −17°C air, bare extremities cooled very rapidly (within 8 min) despite a normal core temperature of 37.2–37.3°C (by providing >10 clo of body clothing insulation), whereas in the present study we reported comfortable extremity temperatures for a similar ambient condition and core temperature (see Figs. 2 and 5). The key difference between Veghte's study and the present study is that in the present study the extremities were kept warm because of active heating on the torso that triggered vasodilation in the extremities, whereas in Veghte's study there was no active torso heating and therefore no excess heat to be dissipated by the extremities to keep the core temperature from rising.

On average, there was no noticeable increase in T_{re} just before an increase in peripheral blood flow or peripheral skin temperature as was observed in some past studies (33, 35, 39). Instead, T_{re} remained stable, on average, during the entire cold exposure. Perhaps an increase in T_{re} was not observed because, during the cold exposure, the rate of heat dissipation from the hands and the rest of the area not covered by the vest was greater than the heat dissipated from the hands of subjects exposed to much warmer temperatures in other studies. The larger temperature gradient between the air and the hand surface temperature of the subject, for example, may have evoked a greater rate of heat loss. As a result, a potential increase in core temperature was quickly offset by a large heat loss from the hands, and, therefore, no increase in T_{re} was observed. It is also possible that an increase in T_{re} was not observed because it is not a rapidly responding measurement site. Perhaps another core temperature site, such as the esophagus, would have shown an increase.

Finger and Toe Temperature

During THT, the $\overline{T}_{fing}$ in all six subjects tended to cycle up and down during the entire rewarming phase. However, there was much variation in the temperature range of the cycling response from one subject to the next. This $\overline{T}_{fing}$ cycling response may be related to the cold susceptibility differences that exist among subjects (40). In addition, the $\overline{T}_{fing}$ cycling response may also be related to the body's state of heat balance. That is, when the body is in a positive heat balance state, the fingers may remain at a higher $\overline{T}_{fing}$ for a greater period of time to dissipate the surplus heat stored in the body, whereas if the body heat balance is close to zero or some unknown negative body heat balance threshold during torso heating, fluctuations in $\overline{T}_{fing}$ may be observed in an attempt to maintain a steady heat balance state.

Below this unknown threshold, $\overline{T}_{fing}$ decreases to an uncomfortable level. However, a more precise estimation of body heat storage is needed before any conclusions can be drawn in relation to this hypothesis.

During THT, $\overline{T}_{toe}$ cooled at a slower rate relative to the $\overline{T}_{toe}$ cooling rate during CT. During THT, $\overline{T}_{toe}$ was at a comfortable 22°C after 2 h of torso heating, whereas, during CT, $\overline{T}_{toe}$ was at an uncomfortable 12°C after 2 h of torso heating. In addition, $\overline{T}_{toe}$ during THT reached a plateau during the last 30 min of the test, whereas during CT, it showed no sign of a plateau. Torso heating was unable to completely prevent a decrease in $\overline{T}_{toe}$. The observed negative body heat balance may have been able to keep the fingers warm, but a greater delivery of heat to the body or more body clothing insulation is likely necessary to prevent $\overline{T}_{toe}$ from decreasing.

Differences in Left and/or Right T_{fing} Response

On average (n = 6), there was no significant difference ($P \geq 0.05$) between the left and right $\overline{T}_{fing}$ responses during the CT and THT rewarming phases. However, two subjects had significantly different ($P < 0.05$) left and right $\overline{T}_{fing}$ responses during some portions of the THT rewarming phase. In one subject the left-hand $\overline{T}_{fing}$ fluctuated between 7 and 13°C, whereas the right-hand $\overline{T}_{fing}$ fluctuated between 22 and 30°C over the same 30-min period of torso heating. After 30 min, the colder hand warmed up to the same level as the warmer hand, and both hands maintained a similar temperature. Therefore, in some subjects the heat dissipated from the left and right hand may differ tremendously during certain periods of the THT rewarming phase.

Effect of Torso Heating On Cold Extremities

Rapaport et al. (30) reported that adequate heating can rewarm fingers as cold as 12–15°C. In the present study, the temperature of fingers in most subjects fell below 10°C before returning to comfortable levels. In one subject, the $\overline{T}_{fing}$ decreased to a painfully cold 6°C, before rapidly increasing back to 30°C within a 15-min period. Therefore, torso heating is capable of not only rewarming moderately cool fingers but of also reopening the vessels of cold fingers.

Practicality of Torso Heating

The advantages of torso heating over direct hand heating to keep the extremities warm are numerous. First, unlike some reported incidences of insidious hypothermia during direct hand heating (13, 17), the use of torso heating to keep the hands warm did not cause insidious hypothermia to occur during the rewarming phase. Second, finger dexterity may be improved during torso heating compared with direct hand heating because no gloves are worn. Third, torso heating may prove to be a more durable method of hand heating because the heater is worn under a parka, and, as a result, is not prone to the same wear and tear as electrically heated gloves. Last, torso heating is potentially a more efficient form of hand heating because more insulation can practically cover the torso compared with the hand; therefore, less heat is lost to the environment.

In summary, torso heating is a practical, durable, and potentially efficient form of indirect hand heating that may be used in the field by outdoor workers. Torso heating eliminates many of the problems associated with direct hand heating and yet is still able to keep the hands comfortable during cold exposure.

Conclusions

The application of heat to the torso region of the body can keep the fingers and toes at a comfortable temperature (22–25°C) for 2.5-3 h during exposure to −15°C air. The local effects of cold on bare hands can be overcome, provided that there is sufficient heat supplied to the torso.

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